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REPORT
TO THE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SEMIANNUAL STATUS REPORT #3

for
GRANT NAGW-533

LABORATORY EVALUATION AND APPLICATION OF
MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED
CONDITIONS FOR PLANETARY ATMOSPHERES

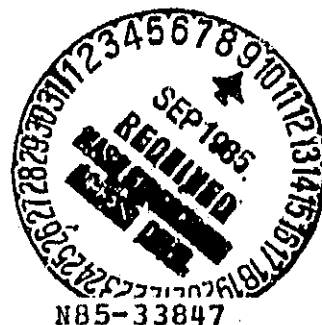
Paul G. Steffes, Principal Investigator

February 1, 1985 through July 31, 1985

Submitted by

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PLANETARY ATMOSPHERES Semiannual Status
Report, 1 Feb. - 31 Jul. 1985 (Georgia Inst. G3/91



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I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often lead to significant misinterpretation of available opacity data. Steffes and Eshleman (1981) showed that under environmental conditions corresponding to the middle atmosphere of Venus, the microwave absorption due to atmospheric SO_2 was 50 percent greater than that calculated from Van Vleck-Weiskopff theory. Similarly, the opacity from gaseous H_2SO_4 was found to be a factor of 7 greater than theoretically predicted for conditions of the Venus middle atmosphere (Steffes and Eshleman, 1982). The recognition of the need to make such measurements over a range of temperatures and pressures which correspond to the periapsis altitudes of radio occultation experiments, and over a range of frequencies which correspond to both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements.

In the initial year of Grant NAGW-533 (i.e., February 1, 1984 through January 31, 1985), this facility was developed, and then operated, in order to evaluate the microwave absorbing properties of gaseous sulfuric acid (H_2SO_4) at 13.4 and 3.6 cm wavelengths, under Venus atmospheric conditions. The

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results were then applied to measurements from Mariner 5, Mariner 10, and Pioneer-Venus Radio Occultation experiments, to determine abundancies of gaseous sulfuric acid in the Venus atmosphere, with accuracies exceeding those achieved with in-situ instruments. Measurements of the microwave properties of the vapors accompanying liquid H_2SO_4 also resulted in more accurate estimates of the vapor pressure behavior of sulfuric acid, which are critical for modeling the behavior and structure of the Venus atmosphere. The results of this work are to be published in a paper entitled, "Laboratory Measurements of the Microwave Opacity and Vapor Pressure of Sulfuric Acid Vapor under Simulated Conditions for the Middle Atmosphere of Venus," which will be published in Icarus. (Note: As specified in the NASA Provisions for Research Grants and Cooperative Agreements, preprints of the original manuscript were sent to the NASA Technical Officer and the NASA Scientific and Technical Information Facility on February 2, 1985. A copy of the revised manuscript, i.e., post-peer review, is attached as Appendix 3.)

During the first six months of the current grant year (February 1, 1985 through July 31, 1985), our work has concentrated on making laboratory measurements of the microwave absorption from gaseous H_2SO_4 at wavelengths from 1 to 3 cm under simulated Venus conditions. Additional measurements of the vapor pressure behavior of sulfuric acid have also been made. Our goal will be to apply these results to radio astronomical observations of Venus which have been made in the wavelength range, in order to better model the structure of H_2SO_4 abundance in the Venus atmosphere, and to resolve temporal variations of its abundance on a planet-wide basis. In addition, we have begun the process of redesigning and refitting the laboratory system so as to permit measurements of the microwave absorptivity of ammonia (NH_3), methane

(CH₄), and other potential microwave absorbers under simulated conditions for the outer planets (Jupiter, Saturn, Uranus, and Neptune). In May, a paper entitled, "Laboratory Measurements of Microwave Absorption from Gaseous Atmospheric Constituents under Conditions for the Outer Planets," was presented at the Conference on the Jovian Atmospheres, held at the Goddard Institute for Space Studies in New York, in which feedback from other experimenters was sought in order to optimize the yield from our outer planets simulations. (See Appendix 1.) This feedback has helped significantly in our design of the outer planets atmospheric simulator.

Our goals for the second half of the current grant year (August 1, 1985 through January 31, 1986) include the analysis and application of the recently obtained 1 to 3 cm wavelength range absorptivity data for gaseous H₂SO₄ in a CO₂ atmosphere. The unique frequency and pressure dependences exhibited by gaseous H₂SO₄ in these wavelength ranges may finally explain what were thought to be inconsistencies between absorption measurements at 13.3 and 3.6 cm wavelengths and those obtained from radio astronomical observations in the 1 to 3 cm wavelength range (see Steffes and Eshleman, 1982). In addition, this new absorptivity data will allow determination of the minimum altitude at which gaseous H₂SO₄ can exist while still being consistent with models for total atmospheric opacity based on radio emission studies. The other major effort will be to complete work on reconfiguring the laboratory so as to allow measurements of the microwave opacity, in the 1 to 20 cm wavelength range, of constituent gases under simulated conditions for the outer planets. We hope to conduct the first of such measurements in December.

II. THE GEORGIA TECH RADIO ASTRONOMY AND PROPAGATION (R.A.P.) FACILITY

The basic configuration of the planetary atmosphere simulator developed at Georgia Tech for use in measurement of the microwave absorptivity of gases under simulated conditions for planetary atmospheres is described at length in the first Annual Status Report for Grant NAGW-533 (February 1, 1984 through January 31, 1985). It is also discussed at length in Steffes (1985), which is attached as Appendix 3. The major new addition made to the laboratory apparatus is a microwave resonator capable of making absorptivity measurements in the 8 to 27 GHz range (1 to 3.7 cm wavelengths). This significantly extends the operating range beyond the previous 1.5 to 8.5 GHz (3.6 to 20 cm) operating range. As shown in Figure 1, the system is currently configured so as to be used in measuring microwave absorption (2 to 27 GHz) from gaseous H_2SO_4 under simulated conditions for the middle atmosphere of Venus (total pressures from 1 to 6 atm, temperatures from 500 to 575 K).

Adding a resonator capable of operating in the 8 to 27 GHz frequency range was more difficult than expected, especially considering the high temperatures and pressures involved. It was decided to use coaxial cable to interconnect the high frequency resonator to the microwave instrumentation, since hermetically-sealed coaxial feed-through connectors were available which would allow operation to 30 GHz while still maintaining the pressure integrity of the chamber. The type of coaxial cable required for the higher frequency resonator was different from that used in the 1.5 to 8.5 GHz range, in that a solid metallic jacket is required to prevent signal leakage, as opposed to the metallic braid used in lower frequency cables. Unfortunately, even when high-temperature solder was used, connector failure occurred for these cables at

temperatures above 500 K. This was due to the extrusion of the PTFE (Teflon) dielectric material within the cable placing mechanical stresses on the connectors. As a result, a limited production air-dielectric cable was obtained which employs a PTFE spline to space the center conductor from the solid metallic outer conductor. The connectors for this specialized cable have been difficult to obtain since special production runs (and accompanying set-up charges) are usually required. Fortunately, we were able to combine the production of our connectors with those from other customers so as to avoid these charges. The result has been a system capable of successfully measuring the microwave absorption from gaseous H_2SO_4 in a CO_2 atmosphere at wavelengths from 1 to 20 cm, at pressures from 1 to 6 atmospheres, and at temperatures from 500 to 570 K. (Lower temperatures can, of course, be achieved but the resulting gaseous H_2SO_4 abundance would be too small so as to provide measurable absorptivity.) It was originally hoped that yet another resonator could be placed within the resonator so as to provide measurements in the 27 to 40 GHz frequency range (0.75 to 1.1 cm wavelength range). Because of the minute losses being measured, a Fabry-Perot type resonator would be required. Unfortunately, the volume required for a Fabry-Perot resonator and the difficulties in coupling signals to it through pressure-sealed waveguides have made that impractical.

The pressure vessel and its accompanying resonators are designed to be usable over an extremely wide range of temperatures. The extremely high temperatures (up to 600 K) developed for the Venus atmosphere simulations by the oven/temperature chamber (see Figure 1) can be replaced by extremely low temperatures created by a freezer/temperature chamber for simulations of the outer planets, as shown in Figure 2. Such a freezer has been recently

procured for use in such measurements. The unit, a Revco/Rheem ULT-7120D, has an internal volume of 193 liters (which is capable of containing the pressure vessel with resonators), and is capable of maintaining temperatures as low as 153 K. Since access to the freezer is through the top of the unit, a special lifting frame and pulley system has been constructed which allows easy movement of the pressure vessel and accompanying resonators in and out of the freezer. The result is a system capable of measuring microwave absorption from 1.5 to 27 GHz (1 to 20 cm wavelength) at pressures to 8 atmospheres and at temperatures as low as 153 K. The minimal measurable absorption absorptivity, or sensitivity, for this system when operated at 170 K is shown in Figure 3, as a function of frequency.

Another more critical limitation on how low the temperatures can be taken (while still being able to measure microwave absorption) is the saturation vapor pressure of the gas being tested. As shown in Table 1, the lowest temperature for which sufficient quantities of gaseous NH_3 would still exist so that the microwave absorption in an H_2 atmosphere would be measurable would be approximately 155 K.

A final critical issue which greatly affects the use of the simulator in outer planets simulations is the use of hydrogen (H_2) at pressures reaching 8 atmospheres. In previous simulations, small leakages from the pressure vessel presented little or no danger to the experimenters. The use of hydrogen will require a special set of procedures and a special ventilation system to be used. Initial pressure tests of the system, as configured for outer planets simulation, will be conducted with nitrogen (N_2). Not only will this be a safer way to test the system, but it will also allow measurement of the collisional microwave absorption from N_2 , which may be the source of the

3.6 cm (8.4 GHz) opacity detected by Voyager 1 radio occultation studies of the Titan atmosphere. (See Lindal et al., 1985.) We hope to begin these tests by December.

III. RESULTS OF LABORATORY MEASUREMENTS AND THEIR APPLICATION

Our goal for the first six months of the current grant year has been to complete laboratory measurements of the microwave absorption from gaseous H_2SO_4 in the 1 to 3 cm wavelength range, under simulated conditions for the middle atmosphere of Venus, and to obtain additional measurements of the vapor pressure behavior of gaseous H_2SO_4 above liquid sulfuric acid. The additional vapor pressure measurements made have been consistent with the vapor pressure expression derived from earlier data. It should be noted, however, that the expression has been revised from its earlier form to reflect a higher percentage dissociation of the H_2SO_4 vapor above liquid sulfuric acid into H_2O and SO_3 . The complete set of vapor pressure measurements and the best-fit expression are plotted in Steffes (1985). (See Appendix 3, Figure 4.)

The measurements of microwave absorption in the 1 to 3 cm wavelength range are currently being evaluated, but one major result has been the extremely low absorptivity observed in the 1.1 to 1.8 cm wavelength range. For example, measurements made at 21.63 GHz (1.38 cm wavelength) show an opacity for a .36% mixture of gaseous H_2SO_4 in a CO_2 atmosphere (with a total pressure of 6 atmospheres and temperature of 570 K) of less than 9 dB/km. This is far below the opacity predicted by using previous measurements at 2.2 GHz and 8.4 GHz and assuming a simple f^2 dependence such as exhibited by SO_2 and CO_2 . In fact, this even implies that using the measured frequency dependences for the microwave absorption from H_2SO_4 in a CO_2 atmosphere in the

2.2 to 8.4 GHz range to predict absorption at 21.6 GHz (1.38 cm wavelength) would result in overstating the absorption at 1.38 cm by at least a factor of 2.

Such behavior implies that the contribution of gaseous H_2SO_4 to the overall non- CO_2 opacity inferred from radio astronomical observations at the 1.35 cm is minimal. Such a result is not surprising in light of the calculations done by Janssen and Klein (1981) which attribute nearly all of the non- CO_2 opacity at 1.35 cm in the Venus atmosphere to SO_2 . This behavior is likewise consistent with the calculated H_2SO_4 resonance frequencies computed by Poynter. (R. Poynter, J.P.L., personal communication. Note that the results of the resonance calculations are shown in Cimino, 1982.) These calculations are based on rotational constants computed using measurements of H_2SO_4 resonances in the 60 to 120 GHz range by Kuczkowski et al. (1981). It is significant that there is a notable absence of H_2SO_4 resonances in the 15 to 30 GHz frequency range, which would be consistent with our measurements. A computation of the microwave spectrum from H_2SO_4 , made by Allen, which is presented in Cimino (1982), showed significantly more absorption from H_2SO_4 in this same frequency range than we have actually measured. This can be explained by the fact that a pressure-broadened linewidth parameter of 7.2 MHz was assumed to H_2SO_4 in a CO_2 atmosphere. It appears that using a smaller broadening parameter will result in a spectrum which will be consistent with our measurements.

Thus, our laboratory measurements indicate that while radio occultation measurements of 13 and 3.6 cm, and radio astronomical measurements at wavelengths longer than 2 cm, measure absorption which is predominated by gaseous H_2SO_4 ; opacity measured by radio astronomical observations in the 1 to 2 cm

wavelength range is predominated by SO₂ at higher altitudes, and by CO₂ at lower altitudes. We intend to present these results at the October 1985 AAS/DPS meeting.

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

In the first six months of the current grant year, a paper was completed and revised for publication in Icarus, describing results and applications of experiments performed during the first year of the grant (P. G. Steffes, 1985, "Laboratory Measurements of the Microwave Opacity and Vapor Pressure of Sulfuric Acid Vapor under Simulated Conditions for the Middle Atmosphere of Venus," attached as Appendix 3.) In May, a paper was presented at the Conference on Jovian Atmospheres, at the Goddard Institute for Space Studies (New York) entitled, "Laboratory Measurements of Microwave Absorption from Gaseous Atmospheric Constituents under Simulated Conditions for the Outer Planets." (See Abstract, Appendix 1.) This paper described our plans and capabilities for simulating outer planets atmospheres and measuring microwave properties of those atmospheres. Much positive feedback was received with regard to the need for such measurements, and discussions were held with I. de Pater of UC/Berkeley and A. Kliore of JPL regarding application of such data to radio astronomical observations, and Galileo probe measurements, respectively. Contact with both is expected to continue as the measurements are made. Contacts have also been maintained with groups at the Stanford Center for Radar Astronomy (V. Eshleman, director), and JPL (Drs. Michael J. Klein and Samuel Gulkis).

During the second half of the current grant year, an Invited Paper will be presented at the International Association of Meteorology and Atmospheric

Physics (IAMAP) Assembly (August 12, 1985) entitled, "Microwave Absorption from Cloud-Related Gases in Planetary Atmospheres," which summarizes our work over the past 18 months and its applications. In addition, a paper will be presented at the October meeting of the Division of Planetary Sciences of the American Astronomical Society (DPS/AAS) on the complete microwave spectrum of H_2SO_4 in a CO_2 atmosphere (from 1 to 15 cm) and its application to understanding the microwave emission spectrum from Venus. We may also submit a short paper to Icarus on this same subject. We have also maintained contact with our congressional delegation, keeping them aware of our work, and the need for continued support to the solar system exploration program. (See Appendix 2.)

V. CONCLUSION

During the first half of the current grant year (February 1, 1985 through July 31, 1985) we have completed measurements of the microwave absorption from gaseous H_2SO_4 in the 1 to 3 cm wavelength range, as well as having applied results from earlier measurements at 3.6 and 13.4 cm wavelengths to microwave absorptivity data from radio occultation measurements at those wavelengths, in order to derive abundance profiles for gaseous H_2SO_4 . We also completed design and began reconfiguration of the system so as to conduct outer planets simulations.

In the second half of the grant year, we intend to complete the outer planets simulator construction, and make some preliminary measurements of the microwave absorption from nitrogen (N_2) to simulate Titan, and from ammonia (NH_3) in a hydrogen atmosphere (H_2) in order to simulate Jovian atmospheres. We will likewise work on the application of our newly derived 1 to 3 cm H_2SO_4 spectrum to a wide range of radio astronomical data.

VI. REFERENCES

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Janssen, M. A. and Klein, M. J. (1981). Constraints on the composition of the Venus atmosphere from microwave measurements near 1.35 cm wavelength. Icarus 46, 58-69.

Kuczkowski, R. L., Suenram, R. D., and Lovas, F. J. (1981). The microwave spectrum, structure, and dipole moment of sulfuric acid. J. Amer. Chem. Soc. 103, 2561-2566.

Steffes, P. G. and Eshleman, V. R. (1981). Laboratory measurements of the microwave opacity of sulfur dioxide and other cloud-related gases under simulated conditions for the middle atmosphere of Venus. Icarus 48, 180-187.

Steffes, P. G. and Eshleman, V. R. (1982). Sulfuric acid vapor and other cloud-related gases in the Venus atmosphere: abundances inferred from observed radio opacity. Icarus 51, 322-333.

VII. KEY FIGURES

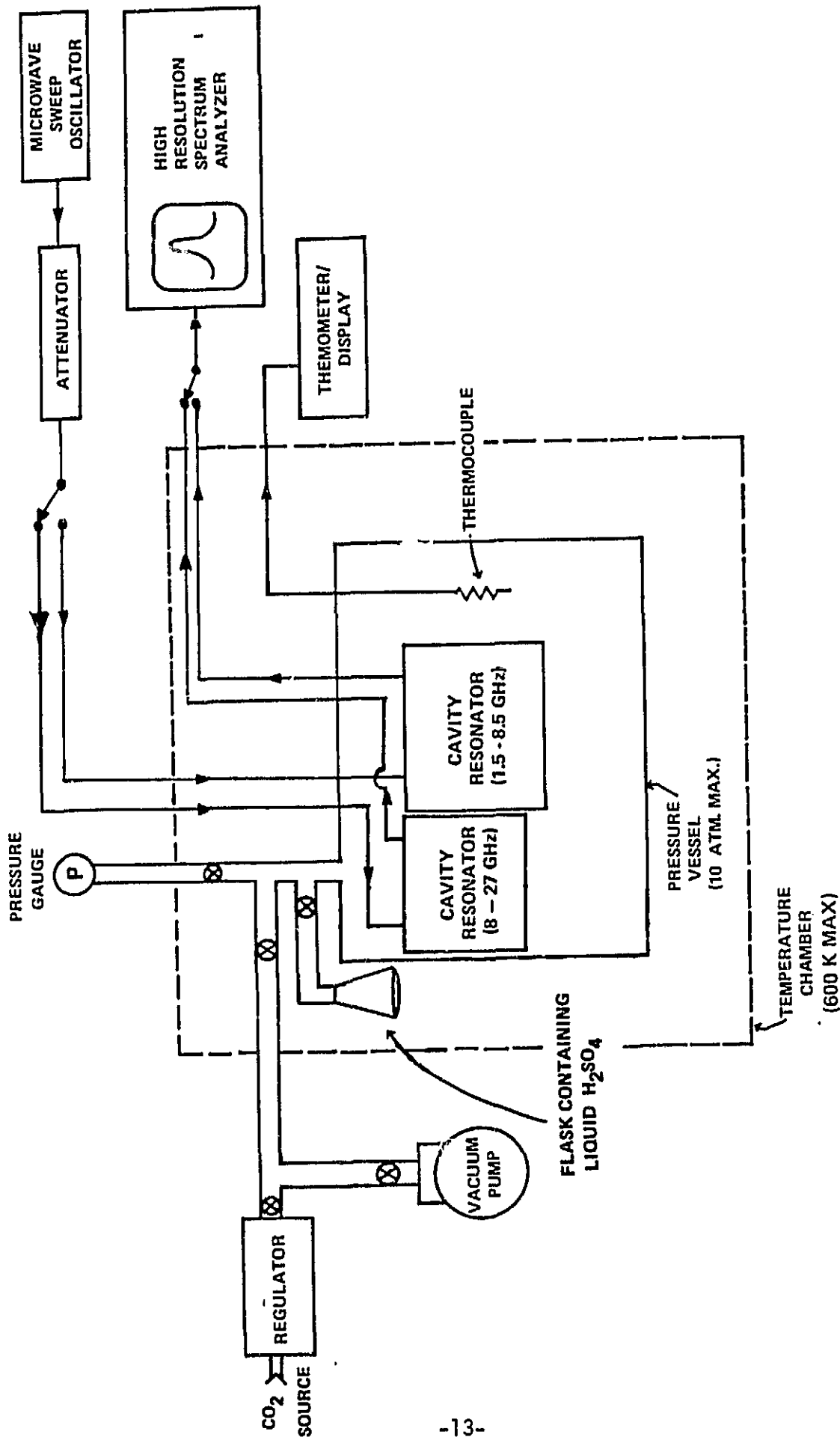


Figure 1: Blockdiagram of updated Georgia Tech Planetary Atmospheres Simulator, as configured for measurements of the microwave properties of gaseous H_2SO_4 under simulated conditions for the Venus atmosphere over the 1 to 20 cm wavelength range.

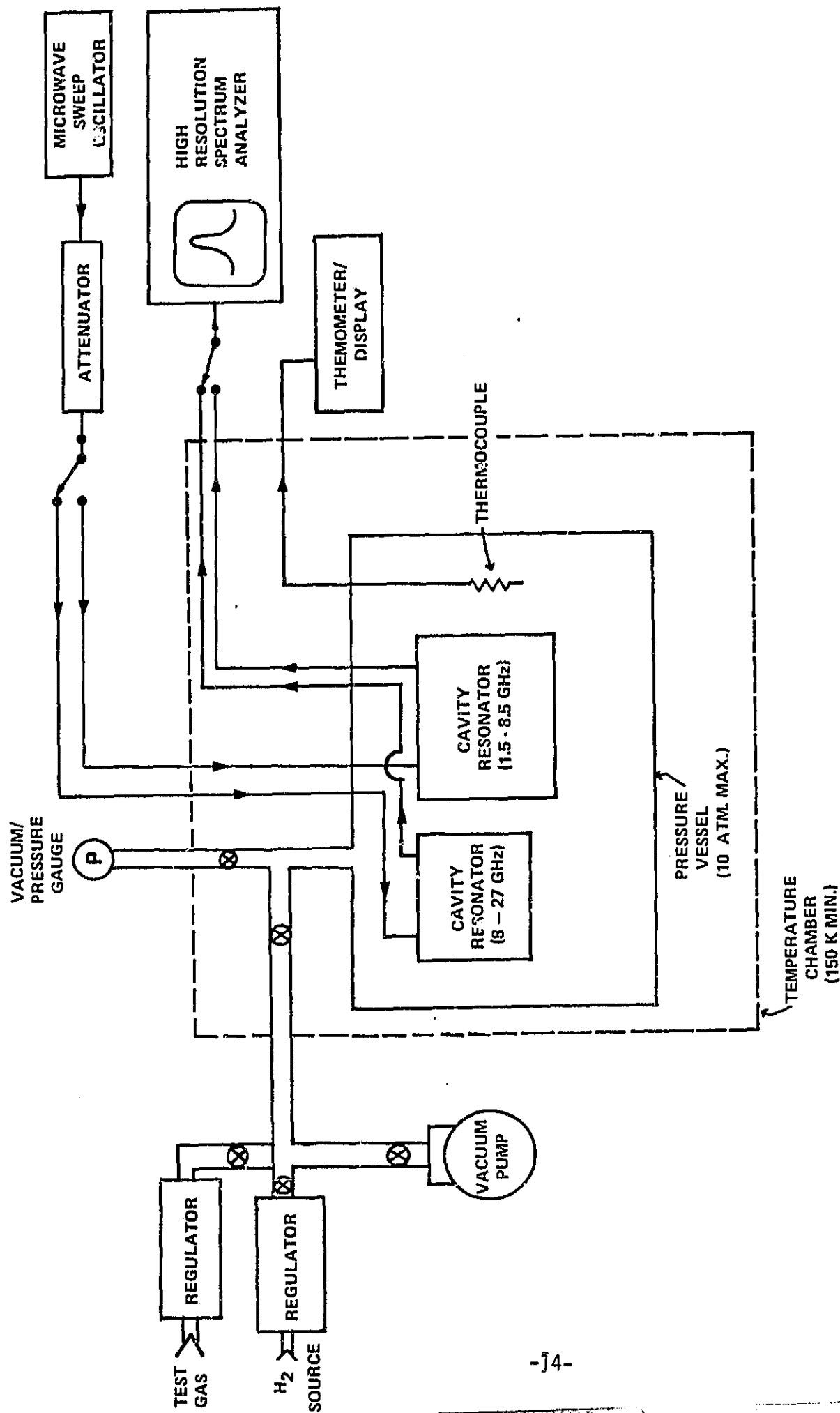


Figure 2: Block diagram of Georgia Tech Planetary Atmospheres Simulator, as configured for measurements of microwave refraction and absorption of gases under simulated conditions for the outer planets.

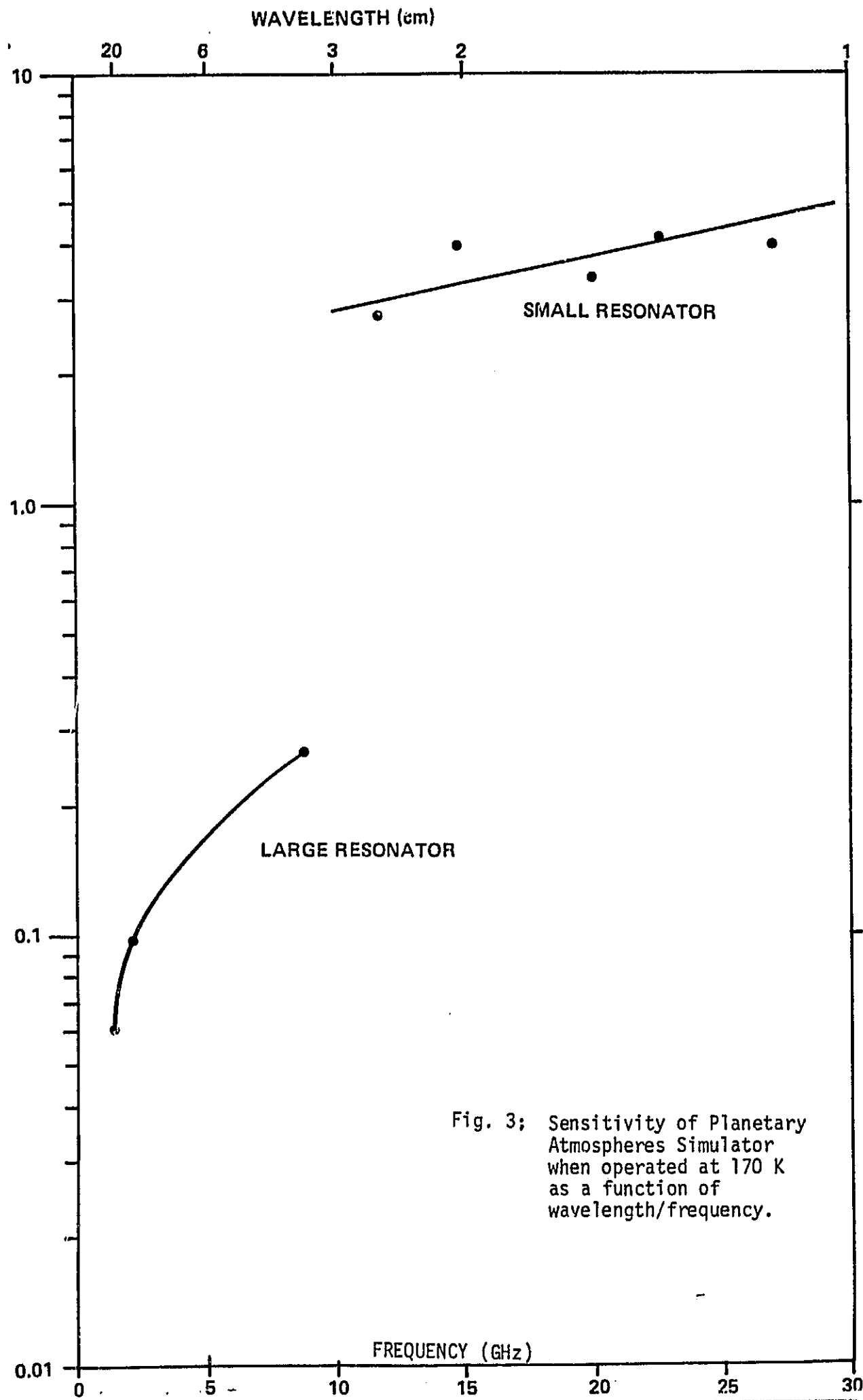


Fig. 3; Sensitivity of Planetary Atmospheres Simulator when operated at 170 K as a function of wavelength/frequency.

TABLE I

MINIMUM GASEOUS ABUNDANCES NECESSARY SO AS TO BE
MEASURABLE BY THE SYSTEM

Constituent Gas	Abundance of Gas in H ₂ atmosphere (6 atm total pressure) required so as to measure microwave absorption at lowest Temperature	Partial Pressure of Gas (in atm.) required so as to exhibit detectable absorption in H ₂ atmosphere. (P _{H₂} = 6 atm.)	Lowest Possible Temperature for which required abundance can be achieved (K)
NH ₃	60 ppm	3.6×10^{-4}	155
H ₂ -H ₂ and H ₂ -He* (collisional)	80% H ₂ : 20% He	6	20
CH ₄ **	33%	2	120
CO	Not Detectable in the 1 to 20 cm range by this system		

* Will provide baseline reference for measurements of other constituents

** The theoretically predicted absorption for methane under these conditions is approximately 80% below the minimum detectable absorption for the system. However, it was felt that this is the largest mixing ratio for which hydrogen broadening would still predominate.

VIII. APPENDICES

APPENDIX I : Abstract of paper presented at the Conference on the Jovian Atmospheres
(Goddard Institute for Space Studies, New York City, May 1985.)

Laboratory Measurements of Microwave Absorption from Gaseous
Atmospheric Constituents under Conditions for the Outer Planets

P. Steffes (Georgia Institute of Technology)

Quite often, the interpretive work on the microwave and millimeter-wave absorption profiles, which are inferred from radio occultation measurements or radio astronomical observations of the outer planets, employs theoretically-derived absorption coefficients to account for contributions to the observed opacity from gaseous constituents. Variations of the actual absorption coefficients from those which are theoretically-derived, especially under the environmental conditions characteristic of the outer planets, can result in significant errors in the inferred abundances of the absorbing constituents. The recognition of the need to make laboratory measurements of the absorptivity of gases such as NH_3 , CH_4 , and H_2O in a predominantly H_2 atmosphere, under temperature and pressure conditions simulating the outer planets' atmospheres, and at wavelengths corresponding to both radio occultation and radio astronomical observations, has led to the development of a facility capable of making such measurements at Georgia Tech. We describe the laboratory measurement system, the measurement techniques, and the proposed experimental regimen for Summer 1985; with the goal of obtaining feedback from interested investigators on the relative priorities of the various proposed measurements to be made on specific constituents at specific wavelengths.

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APPENDIX II:

United States Senate

COMMITTEE ON APPROPRIATIONS
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May 30, 1985

Professor Paul G. Steffes
Georgia Institute of Technology
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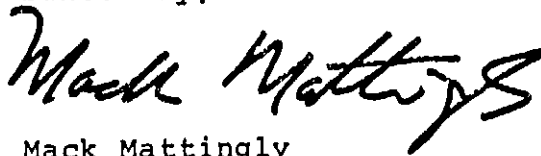
Dear Professor Steffes:

Thank you for contacting me concerning NASA.

I believe that the exploration of space and the utilization of knowledge gained from such efforts would prove to be of inestimable value to all people. It is important that we proceed with the development of space exploration technology and I will support such efforts in the Congress.

Again, thank you for contacting me.

Sincerely,



Mack Mattingly

MM/jbh

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LABORATORY MEASUREMENTS OF THE MICROWAVE OPACITY AND
VAPOR PRESSURE OF SULFURIC ACID VAPOR UNDER SIMULATED
CONDITIONS FOR THE MIDDLE ATMOSPHERE OF VENUS

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Proposed running head: Sulfuric Acid Vapor at Venus

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ABSTRACT

Microwave absorption observed in the 35 to 48 km altitude region of the Venus atmosphere has been attributed to the presence of gaseous sulfuric acid (H_2SO_4) in that region. This has motivated the laboratory measurement of the microwave absorption at 13.4 and 3.6 cm wavelengths from gaseous H_2SO_4 in a CO_2 atmosphere under simulated conditions for that region. As part of the same experiments, upper limits on the saturation vapor pressure of gaseous H_2SO_4 have also been determined. The measurements for microwave absorption have been made in the 1 to 6 atmosphere pressure range, with temperatures in the 500 to 575 K range. Using a theoretically-derived temperature dependence, the best-fit expression for absorption from gaseous H_2SO_4 in a CO_2 atmosphere at the 13.4 cm wavelength is $9.0 \times 10^9 q(P)^{1/2} T^{-3} (\text{dB km}^{-1})$, where q is the H_2SO_4 number mixing ratio, P is the pressure in atmospheres, and T is the temperature in Kelvins. The best-fit expression for absorption at the 3.6 cm wavelength is $4.52 \times 10^{10} q(P)^{0.85} T^{-3} (\text{dB km}^{-1})$. The inferred H_2SO_4 vapor pressure above liquid H_2SO_4 corresponds to $\ln p = 8.84 - 7220/T$ where p is the H_2SO_4 vapor pressure (in atm) and T is the temperature in Kelvins. These results suggest that abundances of gaseous H_2SO_4 on the order of 15 to 30 ppm could account for the microwave absorption observed by radio occultation experiments at 13.3 and 3.6 cm wavelengths. They also suggest that such abundances would correspond to saturation vapor pressure existing at or above the 46 to 48 km range, which correlates with the observed cloud base. It is suggested that future measurements of absorption in the 1 to 3 cm wavelength range will provide additional tools for monitoring variations in H_2SO_4 abundance via radio occultation and radio astronomical observations.

I. INTRODUCTION

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or laboratory measurements of such properties under environmental conditions which are significantly different from those of the planetary atmosphere being studied, often lead to significant misinterpretation of available opacity data. Steffes and Eshleman (1981) showed that under environmental conditions corresponding to the middle atmosphere of Venus, the microwave absorption at 13 cm and 3.6 cm wavelengths due to atmospheric SO_2 was approximately 50 percent greater than that calculated from Van Vleck-Weiskopff theory. Similarly, the opacity from gaseous H_2SO_4 was found to be a factor of 7 greater than theoretically predicted for conditions of the Venus middle atmosphere (Steffes and Eshleman, 1982). The recognition of the need to make such measurements over a range of temperatures and pressures which correspond to the altitudes at which significant opacity has been detected, and over a range of frequencies which correspond to both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements.

In its initial year of operation, this facility has been used to evaluate the microwave absorbing properties and limits to the saturation vapor pressures for gaseous sulfuric acid (H_2SO_4) under simulated conditions for the middle atmosphere of Venus. This paper describes the methodology and results

of laboratory measurements of the absorptivity of gaseous H_2SO_4 in a primarily CO_2 atmosphere at wavelengths corresponding to those used in spacecraft radio occultation experiments (13.4 and 3.6 cm) and for pressures at which these experiments detected significant atmospheric opacity. Also, we describe the results of measurements of the saturation vapor pressure of sulfuric acid. We also discuss the effect these measurements have on modeling H_2SO_4 in the Venus atmosphere. These results are then applied to measurements from Mariner 5, Mariner 10, and Pioneer-Venus Radio Occultation experiments, to determine limits on abundances of gaseous sulfuric acid in the Venus middle atmosphere. We conclude by outlining plans for laboratory measurements of the opacity of gaseous H_2SO_4 at shorter wavelengths (1-3 cm) and for application of these measurements to a wider range of absorptivity data.

II. EXPERIMENTAL APPROACH

The experimental approach used to measure the microwave absorptivity of gaseous H_2SO_4 in a CO_2 atmosphere is similar to that used previously by Steffes and Eshleman (1981 and 1982). As can be seen in Figure 1, the absorptivity is measured by observing the effects of the introduced gas mixture on the Q, or quality factor, of a cavity resonator at its particular resonances near 2.24 GHz and 8.42 GHz. The changes in the Q of the resonator which are induced by the introduction of an absorbing gas mixture can be monitored by the high resolution microwave spectrum analyzer, since Q is simply the ratio of the cavity resonant frequency to its half-power bandwidth. For relatively low-loss gas mixtures, the relation between the absorptivity of the gas mixture and its effect on the Q of the resonator is straightforward:

$$\alpha = (Q_L^{-1} - Q_C^{-1})\pi/\lambda \quad (1)$$

where α is absorptivity of the gas mixture in Nepers km^{-1} . (Note, for example, that an attenuation constant or absorption coefficient or absorptivity of 1 Neper $\text{km}^{-1} = 2$ optical depths per km (or km^{-1}) $= 8.686 \text{ dB km}^{-1}$, where the first notation is the natural form used in electrical engineering, the second is the usual form in physics and astronomy, and the third is the common (logarithmic) form. The third form is often used in order to avoid a possible factor-of-two ambiguity in meaning.) Q_L is the quality factor of the cavity resonator when the gas mixture is present, Q_C is the quality factor of the cavity resonator in a vacuum, and λ is the wavelength (in km) of the test signal in the gas mixture.

In order to obtain a gas mixture with a sufficient amount of H_2SO_4 vapor so that the microwave absorption is detectable, the system must be operated at temperatures exceeding 450 K. While this is suboptimal in that the temperatures at the altitudes where radio occultation experiments have detected microwave opacity range from 350 K to 450 K, temperature dependences measured for similar gases (such as SO_2) can be used to estimate temperature effects in that range. Two different approaches are used to infer H_2SO_4 vapor pressure. With the first, the volume of liquid sulfuric acid which is vaporized to generate the gaseous H_2SO_4 is determined to a high accuracy (up to $\pm 0.005 \text{ ml}$). It is then possible to compute an upper limit for the partial pressure of gaseous H_2SO_4 using the ideal gas equation, the measured change in liquid volume, and published densities for H_2SO_4 liquid. The second method for accurately determining amounts of liquid-derived vapors measures the refractivity of those vapors. Since the index of refraction (relative to unity) is proportional to the vapor abundance, the system's ability to accurately measure the

refractivity of such vapors can also be used to infer the relative vapor abundance/pressure. Note that it is not yet possible to use this approach for accurate determination of the absolute vapor pressure from gaseous H_2SO_4 , since accurate refractivity data for gaseous H_2SO_4 is not currently available. While neither method is able to accurately resolve dissociation of H_2SO_4 into H_2O and SO_3 , an upper limit for H_2SO_4 vapor abundance can be inferred, using the first method, which is accurate to ± 2 percent at a temperature of 500 K.

III. MEASUREMENT TECHNIQUE

As shown in Figure 1, a flask is filled with a precisely known volume of liquid sulfuric acid (99 percent by weight) at room temperature. For nearly all of the experiments, the initial volume used was 2.5 ml (measured at room temperature). Smaller quantities were also tried, with no significant difference in results. The volume measurements are made using a 1 ml syringe with .01 ml gradations. For volumes less than 1 ml, repeatable accuracies of better than .005 ml have been obtained. The entire system is then heated and allowed to thermally stabilize at the chosen experimental temperature (approximately 500-575 K), which requires approximately six hours. The temperature is monitored using a thermocouple which is placed in the center of the pressure vessel, near the microwave resonator, which is one of the coldest places in the system. Thermal equilibrium within the system is achieved by preheating the system for 6 to 8 hours before beginning the experiments. Since the thermal time constant is approximately 2 hours and 15 minutes, this assures a relatively constant temperature within the chamber after heating. Another technique used in monitoring the heating of the resonator within the chamber is to monitor the resonant frequencies of the resonator. As the

resonator is heated, the resonant frequencies drop due to thermal expansion. Thus, when thermal stability is reached, the resonant frequencies likewise stabilize. After thermal stability is reached, a vacuum is drawn in the pressure vessel containing the microwave cavity resonator, and the bandwidth and center frequency of the 13.4 cm and 3.6 cm resonances are then measured. A valve is then opened which allows the sulfuric acid vapor eluting from the flask to fill the pressure vessel (0.031 cubic meters of open volume with resonator in place) and reach vapor pressure equilibrium with the liquid H_2SO_4 . Note that all components which contact the gaseous sulfuric acid are maintained at the same temperature as the flask, so as to avoid condensation. In addition, because of the high temperatures and corrosive vapor involved, all tubing, valves, and the pressure chamber itself are fabricated from stainless steel. Gaskets and cables are fabricated from either viton or PTFE. These steps not only insure the survival of components under the test conditions, but also reduce possible reactions of the components with the sulfuric acid vapor and possible outgassing of vapors related to the materials from which the components are fabricated.

As H_2SO_4 vapor fills the chamber, changes in the resonance center frequency are observed. These changes, which reach over 400 kHz at the 13.4 cm resonance, are related to the H_2SO_4 vapor abundance. After approximately 10 minutes, the frequency shift ceases, as vapor pressure equilibrium is reached. The valve to the reservoir flask is then closed, and CO_2 is admitted to the chamber containing the H_2SO_4 vapor. For this experiment, a total pressure of 6 atm was used. The CO_2 gas is admitted to the chamber at a sufficiently slow rate so as not to significantly affect the temperature within the chamber. The bandwidth of the cavity is then measured and compared

with its value when the chamber was evacuated in order to determine the absorptivity of the $\text{CO}_2/\text{H}_2\text{SO}_4$ gas mixture at 6 atm total pressure. The total pressure is then reduced to 4 atm by venting, and the bandwidth is again measured. Subsequent measurements are likewise made at lower pressures in order to determine absorptivities at those pressures. The pressure vessel is then evacuated and the bandwidth again measured so as to assure no variation (either due to thermal shift or chemical reaction) of the Q of the evacuated resonator has occurred. After the system has been allowed to cool, the volume of the remaining sulfuric acid liquid (at room temperature) is measured and compared with the initial volume measured (at room temperature) in order to set an upper limit on H_2SO_4 vapor present in the gas mixture tested. This approach has the advantage that the same gas mixture is used for the absorptivity measurements at the various pressures. Thus, even though some uncertainty may exist as to the mixing ratio of the initial mixture, the mixing ratios at subsequent pressures will be the same, and thus the uncertainty for any derived pressure dependence will only be due to the accuracy limits of the absorptivity measurements, and not uncertainty in the mixing ratio. (This assumes that the mixing ratio is small, so that foreign-gas broadening predominates, as is the case for our measurements.) Similarly, measurements of the frequency dependence of the absorptivity from a $\text{CO}_2/\text{H}_2\text{SO}_4$ mixture will likewise be immune to mixing ratio uncertainty, as long as foreign-gas broadening predominates.

While the overall equipment configuration and experimental approach for these measurements is similar to that used by Steffes and Eshleman (1982) for measurement of the absorptivity of gaseous H_2SO_4 in a CO_2 atmosphere at a single pressure and temperature, several major differences between the current system and those used previously exist:

- (1) The pressure containment vessel is large enough (0.33 m diameter, 0.38 m height) so that it will allow the use of resonators which operate at frequencies as low as 1.5 GHz (20 cm wavelength), and yet still be heated to temperatures over 500 K while maintaining pressures up to 10 atmospheres.
- (2) The resonator used to measure absorption in the 2.2 to 8.4 GHz range (13.4 to 3.6 cm wavelengths) exhibits a higher "quality factor," or Q , due to special construction techniques. These techniques include the use of stainless steel to construct the resonator, and then plating with nickel, copper, and silver. This not only maximizes Q , but insures that the Q will remain high in spite of drastic thermal shifts. As a result, the system sensitivity is greater, resulting in lower measurement uncertainties.
- (3) The use of a digitally-refreshed spectrum analyzer further serves to increase the sensitivity of the system. As a consequence, when measurements are to be made of the microwave absorption from gases which are obtained from liquid-derived vapors, a smaller amount of source liquid can be used, allowing operation at lower temperatures without condensation.
- (4) Uncertainties of mixing ratios of gases obtained from liquid-derived vapors have been greatly reduced for two reasons. First, the amounts of liquid used to generate these gases can be determined with a volume accuracy of up to ± 0.005 ml. Thus, when an amount of liquid becomes vapor, it becomes possible to accurately compute an upper limit for the partial pressure due to that vapor using the ideal gas equation and the measured change in liquid volume.

Secondly, the high sensitivity and high stability of the microwave spectrum analyzer allow accurate measurements of the refractivity of introduced vapors, which can also be used to infer relative vapor abundance.

IV. MEASUREMENT RESULTS

A wide range of laboratory measurements of the microwave absorbing properties of gaseous H_2SO_4 in a predominantly CO_2 atmosphere have been made under temperature and pressure conditions (temperatures to 575 K and pressures to 6 atm.) simulating the middle atmosphere (35-50 km altitude) of Venus. The measurements reported here were made at frequencies of 2.24 and 8.44 GHz (13.4 and 3.6 cm wavelengths) in order to allow direct application to absorptivity data from Pioneer-Venus, Mariner 5, and Mariner 10 radio occultation experiments. However, measurements over a wider range of wavelengths are currently underway.

Since absorptivity at radio frequencies is generally directly proportional to the abundance (either by number or by volume) of the absorbing constituent, the results of our measurements, shown in Figures 2 and 3, are plotted as absorptivities normalized by H_2SO_4 mixing ratio. Figure 2 shows the normalized absorptivity of gaseous H_2SO_4 in a CO_2 atmosphere (taken at 570 K temperature and at 2.24 GHz frequency) as a function of pressure. Similarly, Figure 3 shows similar measurements taken around 525 K and at a frequency of 8.42 GHz. The H_2SO_4 mixing ratios used to normalize the plots were obtained by dividing the vapor pressure data from Figure 4 (which were obtained by the measurement techniques described in Sections II and III) by the sum of the H_2SO_4 vapor pressure plus the CO_2 vapor pressure when the

mixture was formed (6 atm for our experiments). The error bars shown in Figures 2 and 3 represent 1σ errors in the absorptivity measurements, but do not include uncertainties in mixing ratios. Since the same mixing ratio is used for all measurements at a given temperature, a small scale factor error might be present.

It should be noted that while the techniques used to set upper limits on the H_2SO_4 vapor pressure obtained from the 99.0 percent concentration (by weight) liquid H_2SO_4 solutions used can determine these limits quite accurately, they do not represent direct measurement of H_2SO_4 vapor pressure. For the results presented in Figure 4, it is assumed that 47 percent of the vaporized H_2SO_4 dissociates to form gaseous SO_3 and H_2O , as computed by Gmitro and Vermeulen (1964) for 99% solutions. Since neither SO_3 nor H_2O exhibit measurable microwave absorption in the quantities which would be present (see Steffes and Eshleman 1981, and Ho et al. 1966), this dissociation results in an increase in the measured absorptivity (normalized by number mixing ratio) due to gaseous H_2SO_4 . Also it is assumed that the portion of the vaporized liquid which actually becomes gaseous sulfuric acid is proportional to the number density of sulfuric acid molecules in the liquid solution. It should also be noted that the vapor pressures plotted are for a 99 percent (by weight) solution of sulfuric acid, except for the 4 points taken at the lowest temperatures, where a 95.9 percent solution was used. The predicted difference in H_2SO_4 vapor pressure caused by this lower concentration is a reduction of less than 25 percent (see Gmitro and Vermeulen, 1964). Thus, it was felt that this reduction would only slightly affect our best fit expression plotted for the temperature dependence of the H_2SO_4 vapor pressure:

$$\ln p = 8.84 - 7220/T \quad (2)$$

where p is the H_2SO_4 vapor pressure in atmospheres and T is the temperature in Kelvins. The error bars shown for each point in Figure 4 represent 1σ variations in temperature (horizontal axis) and in inferred vapor pressure (vertical axis). The variations in temperature measurement result from limits on thermocouple accuracy, while variations in inferred vapor pressure result from the accuracy limitations on the volume measurement of the vaporized liquid.

Another potential source of error could be opacity from molecules, other than H_2SO_4 , H_2O , or SO_3 which accompany sulfuric acid vapor. Two such molecules would be the sulfuric acid dimer (i.e., $2\text{-H}_2\text{SO}_4$) and the sulfuric acid hydrate ($\text{H}_2\text{SO}_4 \cdot \text{H}_2\text{O}$). However, electric deflection studies by Kay (1984) concluded that H_2SO_4 dimers are nonpolar, which would suggest little or no microwave opacity. Additionally, no hydrated sulfuric acid molecules were detected above liquid sulfuric acid at 593 K, suggesting a minimal abundance of such molecules.

In Figures 2 and 3, best-fit multiplicative expressions are plotted for the 13.4 and 3.6 cm absorption from gaseous H_2SO_4 . (Note: By "multiplicative" we mean a function which is directly proportional to some power of pressure.) Combining the measured pressure dependence, with an estimated thermal dependence of T^{-3} (a $T^{-3.1}$ dependence has been measured for SO_2 , see Steffes and Eshleman, 1981) gives the following result for absorption from gaseous H_2SO_4 in a CO_2 atmospheres at the 13.4 cm wavelength:

$$\alpha_{13} (\text{dB km}^{-1}) = 9.0 \times 10^9 q(P)^{1/2} T^{-3} \quad (3)$$

where q is the H_2SO_4 number mixing ratio, P is the pressure in atmospheres, and T is the temperature in Kelvins. A similar expression for absorption from

gaseous H_2SO_4 in a CO_2 atmosphere at the 3.6 cm wavelength has also been estimated:

$$\alpha_{3.6} (\text{dB km}^{-1}) \approx 4.52 \times 10^{10} q(P)^{0.85} T^{-3} \quad (4)$$

Inspection of these results shows several significant findings:

- (1) A new relation for H_2SO_4 vapor pressure has been developed which generally confirms the work of Roedel (1979) and Ayers et al. (1980) in that the vapor pressures inferred are a factor of ten below those predicted by Gmitro and Vermeulen (1964). However, the findings with regard to the temperature dependence of the H_2SO_4 vapor pressure are different enough from previous work so as to significantly affect the saturation abundances and cloud formation altitudes which one would predict for the Venus atmosphere. Clearly, additional measurements in the 350-450 K range are needed.
- (2) While generally confirming the initial laboratory measurements made by Steffes and Eshleman (1982) of H_2SO_4 vapor absorption at a single temperature and pressure, it has been found that the microwave absorption of H_2SO_4 in a CO_2 atmosphere has a significant pressure dependence at both the 13 cm and 3.6 cm wavelengths. This is in sharp contrast to the theoretical calculation presented in Cimino (1982).
- (3) Frequency dependences which vary significantly with pressure have been found for the 3-13 cm wavelength absorption from gaseous H_2SO_4 , ranging from $f^{1.23}$ at 1 atm pressure to $f^{1.7}$ at 6 atm pressure. This will significantly effect comparisons of radio occultation data with radio astronomical data from Venus.

- (4) Simple multiplicative expressions for the absorption from gaseous H_2SO_4 in a CO_2 atmosphere at 13 cm and 3.6 cm wavelengths have been developed which are highly useful in converting microwave absorptivity profiles to H_2SO_4 abundance profiles.

In addition to the measurements at 13 cm and 3.6 cm wavelengths, measurements in the 1 to 3 cm wavelength range are currently being conducted and should yield similar valuable data for interpretation of a wide range of radio astronomical data.

V. APPLICATION OF LABORATORY RESULTS TO VENUS OPACITY DATA

A wide range of analytical studies of the Venus atmosphere based on the laboratory data has now begun. These studies cover an area which is so wide that complete documentation would be difficult at this time. Examples of application of the data can be seen in Figures 5 and 6. Figure 5 shows the 13.4 cm wavelength microwave absorption which would arise from a 13.5 ppm abundance of gaseous H_2SO_4 in the middle atmosphere of Venus which condenses to form clouds at 48 km altitude. It can be seen from this figure that gaseous H_2SO_4 is the predominant microwave absorber in the 35 to 48 km altitude range as compared to other absorbing constituents. For this comparison, we use equation (3) to compute the opacity from gaseous H_2SO_4 . For SO_2 , H_2O , and CO_2 , measured absorption coefficients from Steffes and Eshleman (1981) and Ho et al. (1966) are used. For liquid H_2SO_4 , we employ opacities from Cimino et al. (1980). It can also be seen from this figure that abundances on the order of 15 to 30 ppm could account for most of the 13 cm absorption measured in a number of radio occultation measurements. In

addition, it should be noted that if the frequency dependences measured in the 3 to 13 cm wavelength range are used to extrapolate to 1.35 cm, the resulting vertical opacity from a 15 to 30 ppm abundance of gaseous H_2SO_4 at altitudes below 48 km would exceed that attributable to constituents other than CO_2 and SO_2 ($\tau_{\text{other}} = 3.6$, for further discussion, see Steffes and Eshleman, 1982). Thus, it is likely that dissociation of gaseous H_2SO_4 occurs at lower altitudes (below 30 km). Actual limits on gaseous H_2SO_4 abundance, based on opacities inferred from 1.35 cm brightness and temperature measurements must await laboratory measurement of the 1.35 cm absorptivity of gaseous H_2SO_4 .

Figure 6 shows abundance of gaseous sulfuric acid, at several altitudes, obtained by attributing all of the 13 cm opacity measured by the 3 radio occultation experiments shown, to gaseous sulfuric acid. Also shown are curves showing saturation vapor abundance as a function of altitude. Note that the vapor will not condense at a given altitude unless its abundance equals or exceeds the saturation abundance. The saturation vapor abundance obtained using vapor pressure data from Gmitro and Vermeulen (1964) would imply that for the $\text{H}_2\text{SO}_4(\text{g})$ abundances shown, no significant cloud formation could occur except at altitudes well above 50 km. This, of course, conflicts with in-situ atmospheric probe findings. (See, for example, Esposito et al., 1983.) The saturation vapor abundance from Ayers et al. (1980) would require cloud formation below the 45 km altitude for the $\text{H}_2\text{SO}_4(\text{g})$ abundance shown, which likewise conflicts with in-situ findings. The saturation abundances inferred from our measurements are consistent with cloud formation in the 46 to 48 km range, for the given abundances of gaseous H_2SO_4 , except for a single peak measurement from the Mariner 10 experiment. However, it should be noted that the average Mariner 10 absorptivity measurements were well below that figure (Lipa and Tyler, 1979).

While the correlation between the inferred abundance of gaseous sulfuric acid (inferred by ascribing to it most of the observed 13 cm opacity in the sub-cloud region) and the abundance required so that saturation, and cloud formation, would begin in the 46 to 48 km altitude range gives further support to the hypothesis that observed 13 cm opacity is indeed caused by gaseous sulfuric acid below the clouds, it cannot be said to constitute proof thereof. However, the strong correlation between the shape of the observed 13 cm opacity profiles (some variations below 48 km altitude, but little measurable opacity above 50 km--see, for example, Fjeldbo et al. (1971) or Cimino (1982)), and the opacity profile shown in Figure 5 gives further evidence to support that theory. A similar correlation exists between observed opacity at 3.6 cm (see Cimino, 1982) and that attributed to gaseous sulfuric acid which follows our saturation abundance curve (see Figure 6) above the 48 km altitude.

Thus, abundances of gaseous sulfuric acid below the main Venus cloud layer on the order of 15-30 ppm are indicated from radio occultation 13 cm absorptivity measurements. However, positional and temporal variations in the measured opacity at 13 cm (from radio occultation experiments) and at 3.6 cm (from radio astronomical and radio occultation experiments) indicate as much as a factor of 2 variation in the gaseous H_2SO_4 abundance in the 30-50 km altitude range. While some portion of these apparent variations in atmospheric opacity may be due to interpretive or calibration inaccuracies, they suggest significant atmospheric changes with time and position. Such variabilities as observed by the relatively localized radio occultation measurements at 13.3 cm and 3.6 cm wavelengths, may be due to global circulation (see Kliore et al., 1984). However, longer term variations of the full

disk brightness temperature at wavelengths shortward of 4 cm may require variations on a global scale, such as might be induced by volcanism. (See, for example, Esposito (1984) or Prinn (1984).) Further study into this issue is being conducted.

VI. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

The laboratory measurements made of the microwave absorption and vapor pressure of sulfuric acid vapor under simulated Venus conditions, when applied to the measured opacities and temperature structure for the Venus atmosphere, give new insights into the abundance and structure of sulfuric acid vapor in the Venus atmosphere. Because of instrumental limitations of in-situ probes (see Von Zahn et al., 1983), this may become the major technique for determining H_2SO_4 abundance profiles in the Venus atmosphere.

Future measurements will allow us to interpret a wider range of microwave absorptivity data, and with higher accuracies. Measurements currently planned or underway include:

- (1) Measurement of absorptivity of gaseous H_2SO_4 in a CO_2 atmosphere (1 to 6 atm total pressure) in the 1 to 3 cm wavelength range.
- (2) Measurement of the temperature dependence of H_2SO_4 microwave opacity.
- (3) Measurement of upper limits for H_2SO_4 vapor pressure in the 350-500 K temperature range, as constrained by system sensitivity.

Completion of these measurements will permit study and interpretation of an extremely wide range of microwave opacity data for the Venus atmosphere, with accompanying results in the area of temporal and spatial constituent abundance variations. Finally, upon completion of these measurements, the system will

be reconfigured so as to allow for microwave absorptivity measurements of several gaseous constituents under simulated conditions for the outer planets. Such measurements can be used to interpret data from Voyager radio occultation experiments, radio astronomical observations of the outer planets, and in the future, radio absorption measurements from the Galileo spacecraft and probe.

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FIGURE CAPTIONS

- Figure 1: Block diagram of atmospheric simulator, as configured for measurements of microwave absorption of gaseous H_2SO_4 under venus atmospheric conditions.
- Figure 2: Measured microwave absorptivity (normalized by number mixing ratio) for gaseous H_2SO_4 in a CO_2 atmosphere as a function of pressure at 2.24 GHz (13.4 cm wavelength). Error bars are $\pm 1 \sigma$. Dashed line represents a best-fit multiplicative expression for absorptivity.
- Figure 3: Measured microwave absorption (normalized by number mixing ratio) for gaseous H_2SO_4 in a CO_2 atmosphere as a function of pressure at 8.42 GHz (3.6 cm wavelength). Error bars are $\pm 1 \sigma$. Dashed line represents a best-fit multiplicative expression for absorptivity.
- Figure 4: Vapor pressure of gaseous H_2SO_4 above liquid sulfuric acid as a function of the inverse of temperature. The illustrated points are from the laboratory measurements. Vapor pressure expressions (dotted lines) from Ayers *et al.* (1980) and Gmitro and Vermeulen (1964) are then compared with a best-fit expression for our measurements (solid line). Error bars for temperature and pressure are $\pm 1 \sigma$.
- Figure 5: Comparative 13.4 cm opacity of several constituents in the middle atmosphere of Venus, assuming the presence of gaseous (g) H_2SO_4 (13.5 ppm), gaseous SO_2 (150 ppm), gaseous H_2O (1000 ppm), CO_2 (95%), and liquid (l) H_2SO_4 (100 mg per cubic meter in the 48 to 50 km altitude range). We assume the cloud-related gases to be depleted above the cloud layer (50 km and above).
- Figure 6: Saturation abundances for gaseous sulfuric acid (H_2SO_4) under conditions for the Venus middle atmosphere. Dashed lines represent saturation abundance data from Ayers *et al.* (1980) and Gmitro and Vermeulen (1964). Solid line represents saturation abundance data from this work. The illustrated points represent the abundances of gaseous H_2SO_4 required to explain radio occultation results at 13 cm from Mariner 5 (Fjeldbo *et al.*, 1971), Mariner 10 (Lipa and Tyler, 1979), and Pioneer Venus Orbit 18 (Cimino, 1982), using the laboratory measurements described.

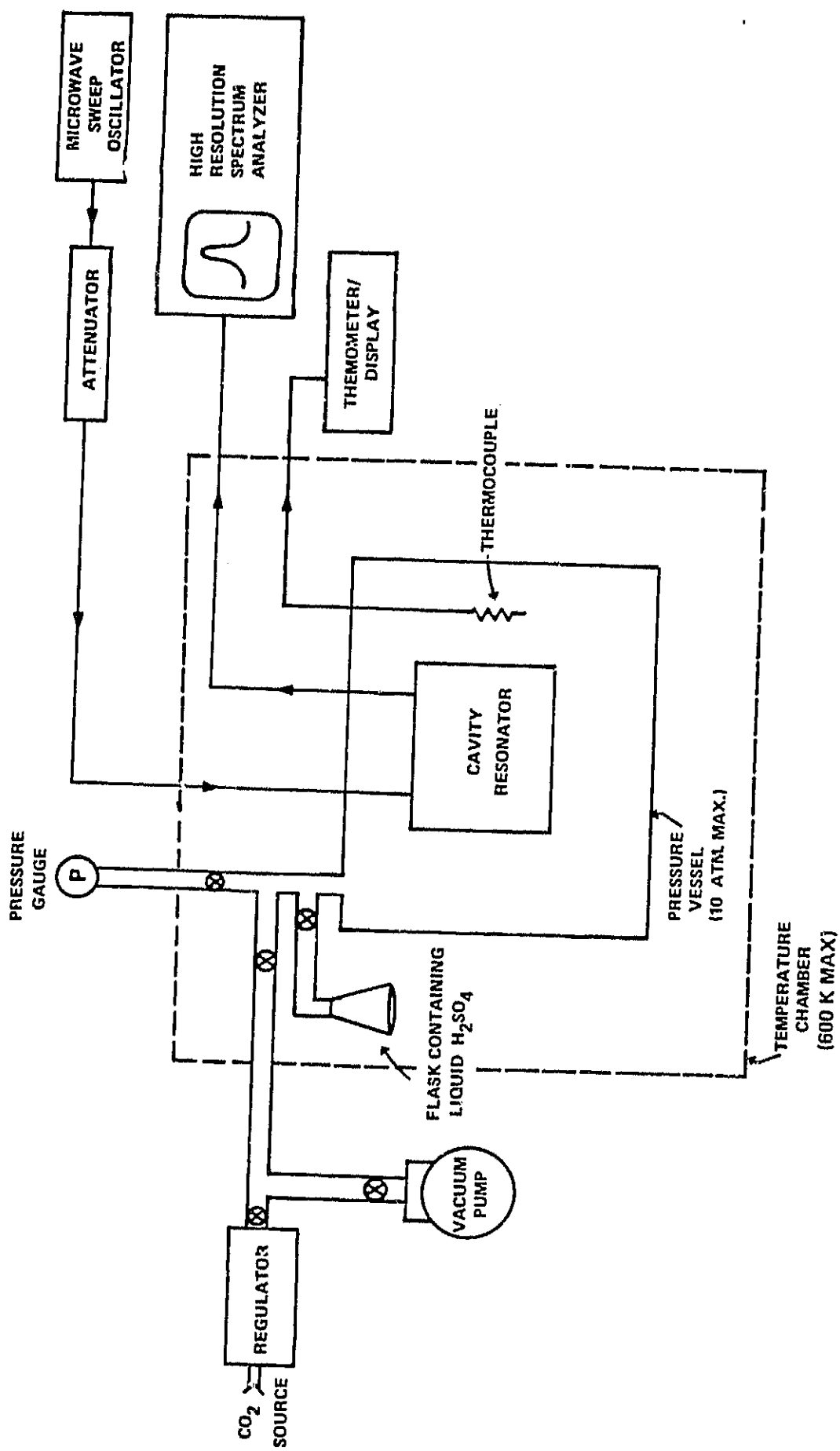


Fig. 1
(Steffes)

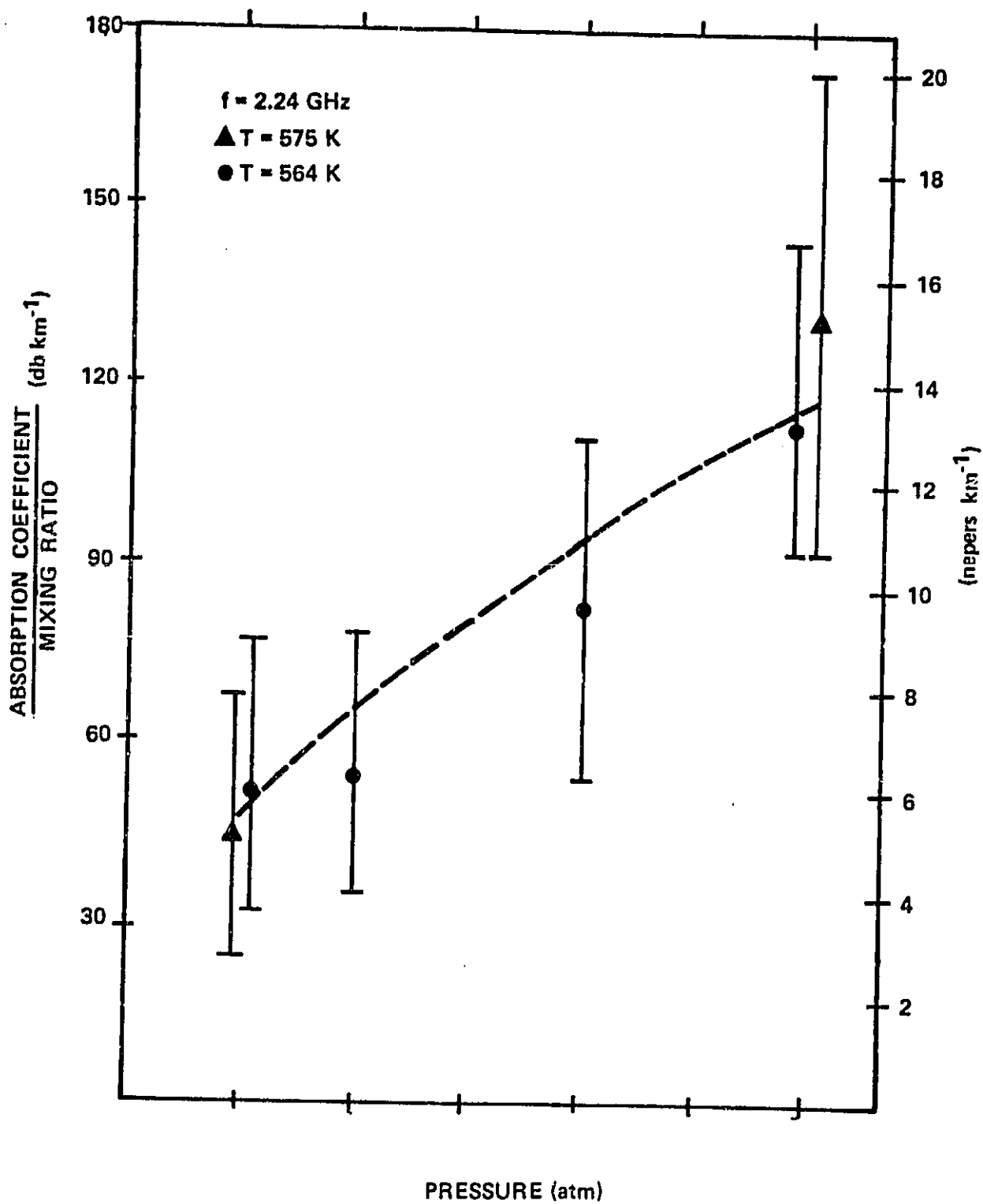


Fig. 2
(Steffes)

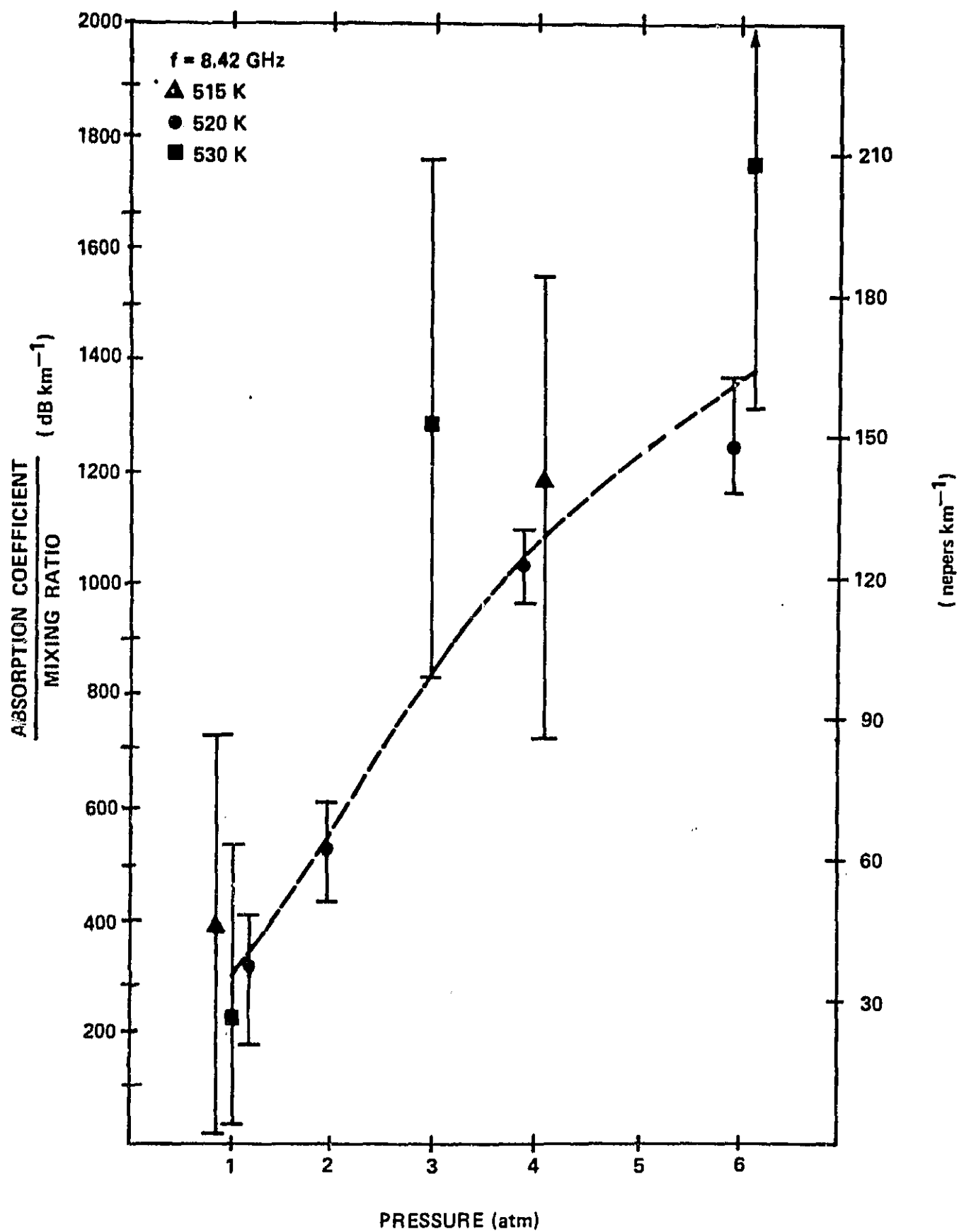


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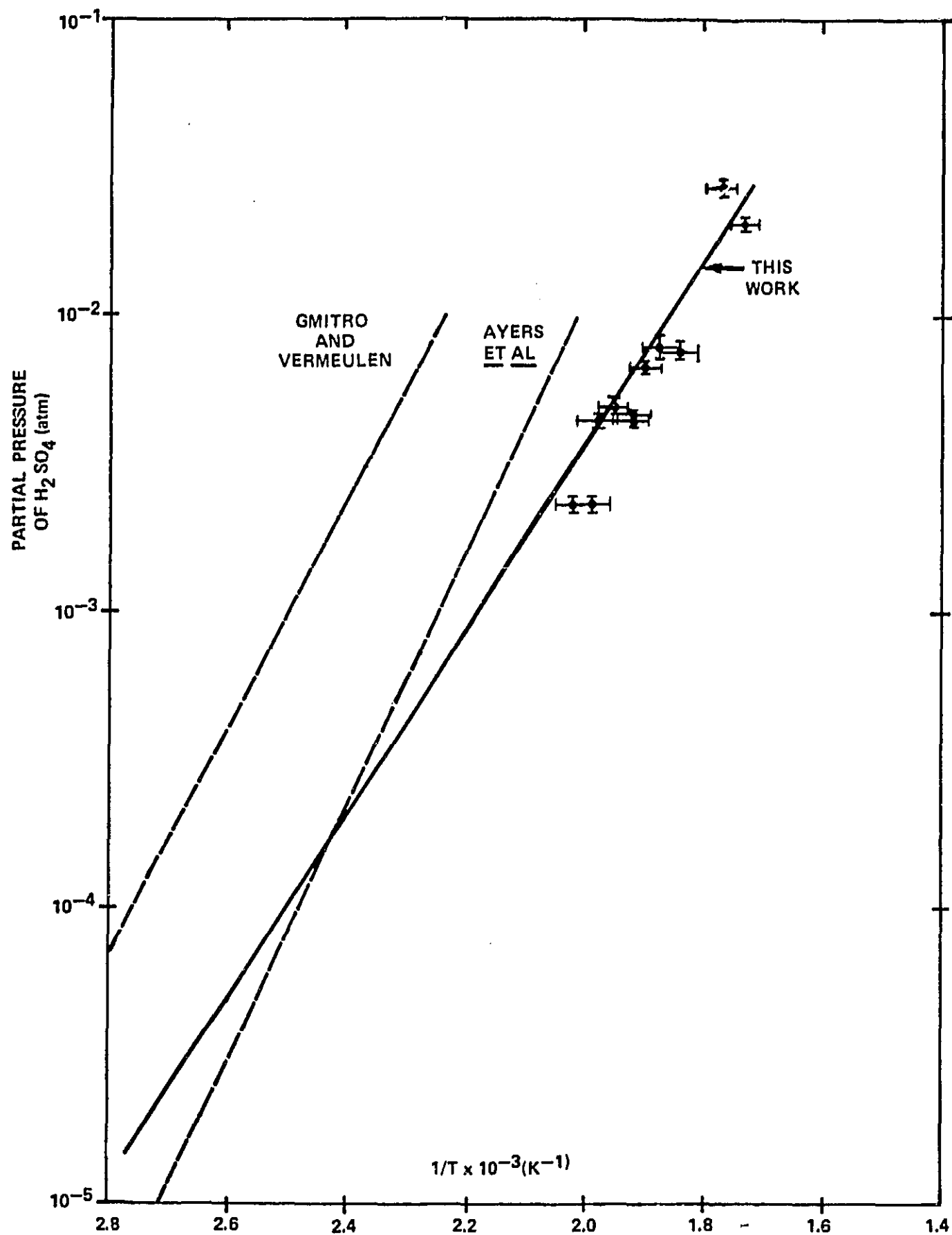


Fig. 4
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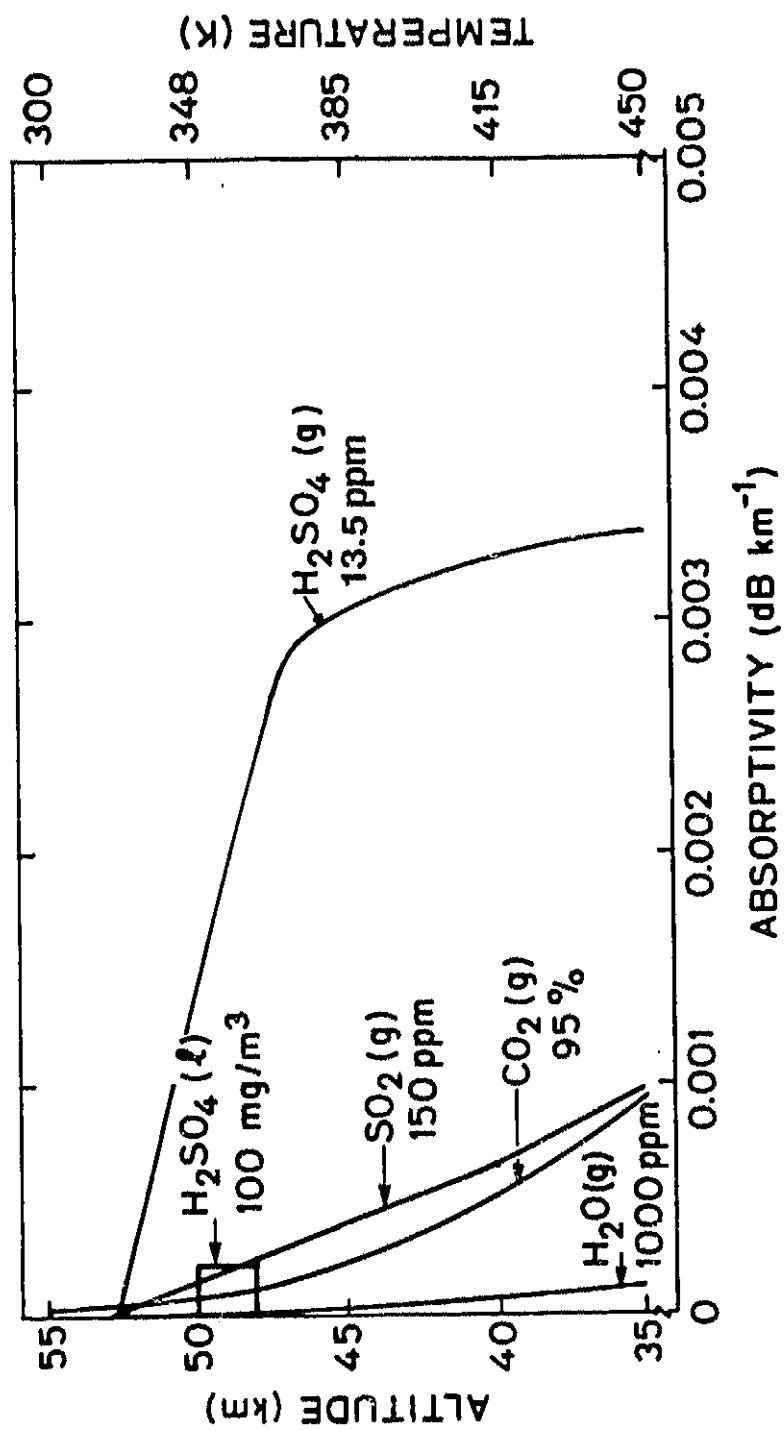


Fig. 5
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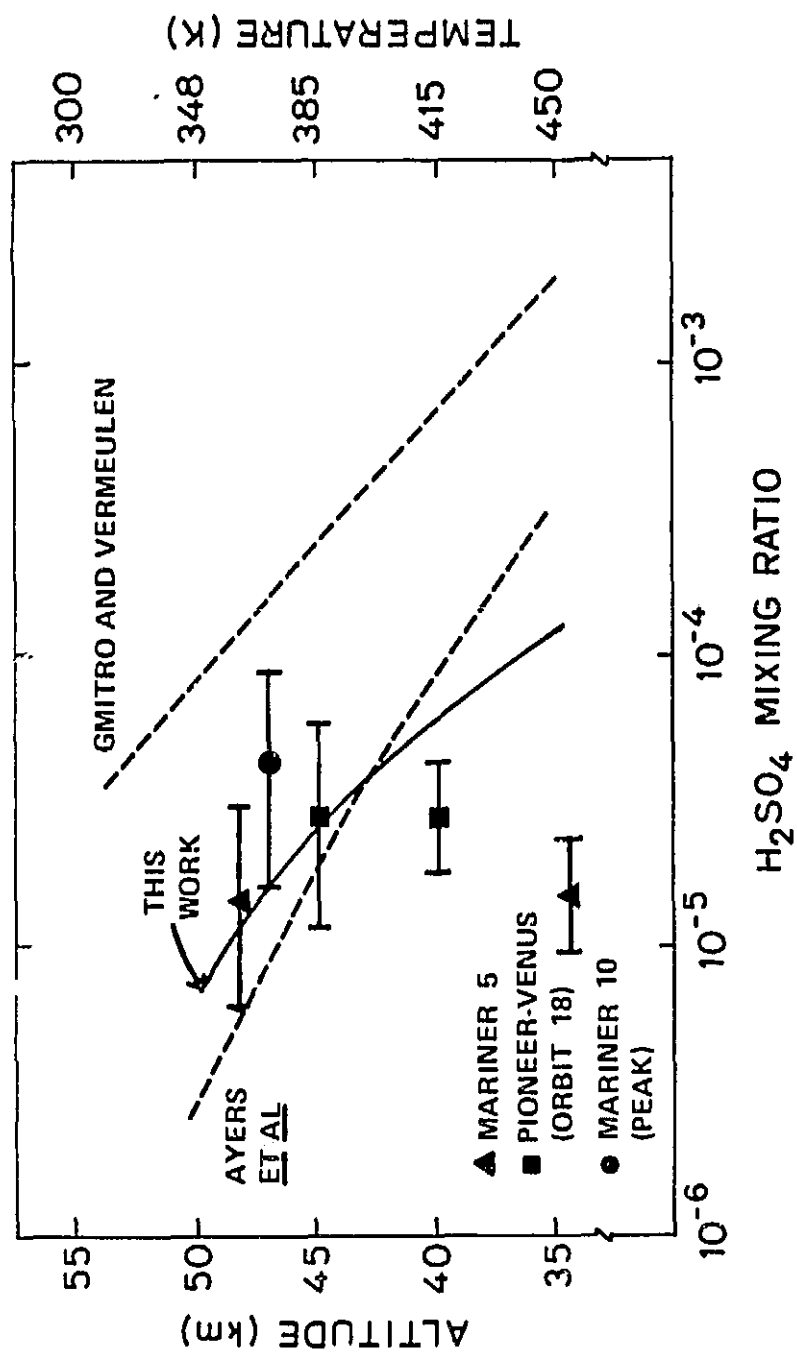


Fig. 6
(Steffes)

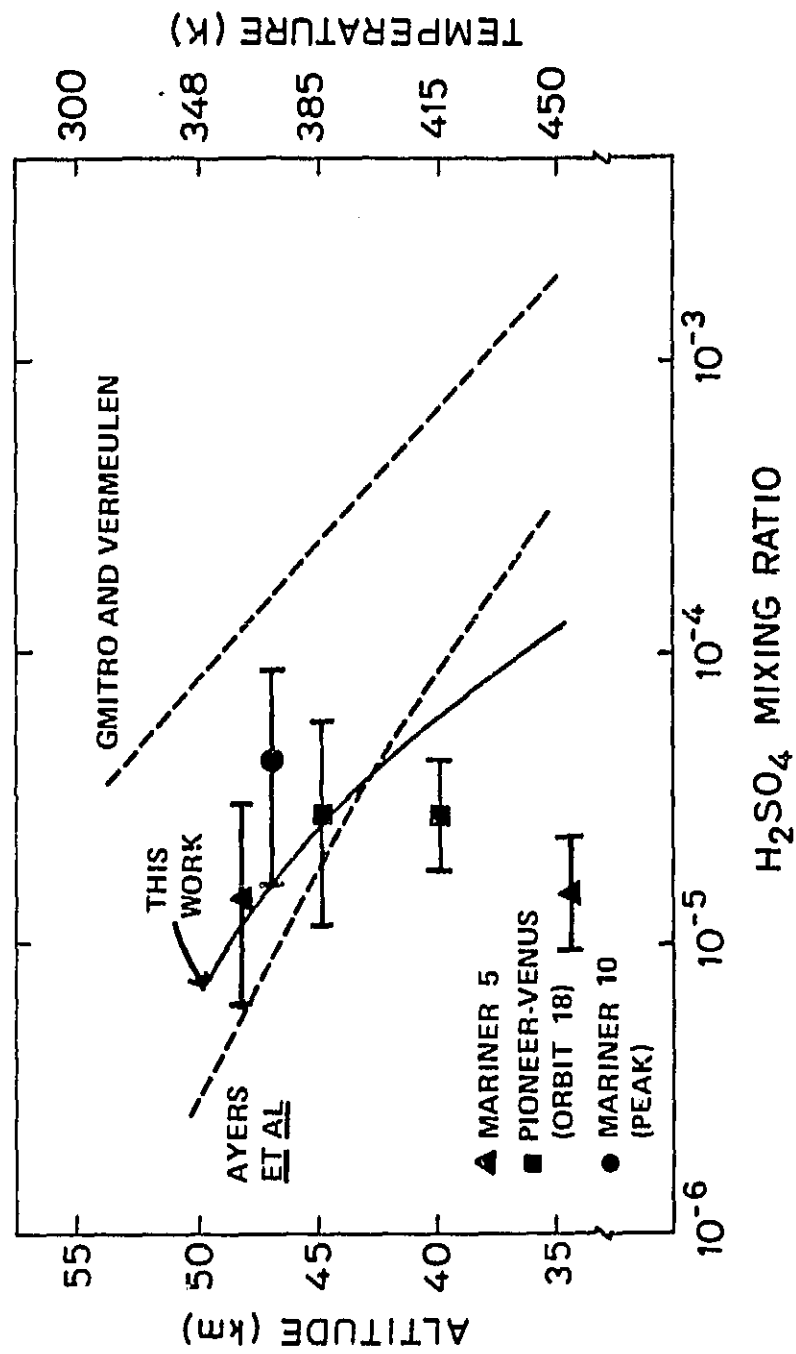


Fig. 6
(Steffes)